Sub-Micron Mechanical Stability of a Prototype Deployable Space Telescope Support Structure

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Presentation Outline

- Background and Motivation for Research in Microdynamics of Deployable Space Structures
- Experimental Measurements on a Prototype Deployable Mirror Support Structure
- Correlation of the Experimental Measurements with a Phenomenological Model
- Conclusions
- Current Research Activities

Experimental observations are presented showing the apparent microstrain stabilization of a deployed structure due to strain relief in hysteretic mechanisms.

Implication is that even lightly preloaded deployed structures can be as stable as materials themselves (i.e., to microstrain levels).

Structural Mechanics are Nonlinear at Small Motions as Well as Large

- **Small Motion Nonlinearities in Joints and Latches**
  - Contact mechanics at preloaded interfaces
  - Microslip friction patterns at small motions
  - Surface asperities even under significant joint preload
  - Freeplay is not a representative nonlinearity for precision structures
- **Small Motion Nonlinearities in Materials**
  - Discontinuous elastic modulus in polycrystalline materials
  - Residual stress in low CTE composite
  - Micromechanics at fiber-matrix interface in composites

The breakdown of linear elasticity at small motions may present a fundamental limit to precision spacecraft performance.

Structural Micro-Nonlinearity in Deployed Structures will Drive Active Control System Requirements

- **Deployment Repeatability**

  "Absolute accuracy of the deployed shape with respect to a ground measurement or gravity-adjusted model"

  - Effected by material long term stability, manufacturing accuracy, and mechanical hysteresis.
  - Drives the dynamic range of the active adjustment system

- **Microdynamics**

  "Small motion nonlinear mechanics of materials and latches."

  - Potential for high frequency sudden release of strain even under near steady mechanical and thermal loads. (e.g., ~<10psi, ~<10 milli °K)
  - Drives the dynamic bandwidth of the active control system

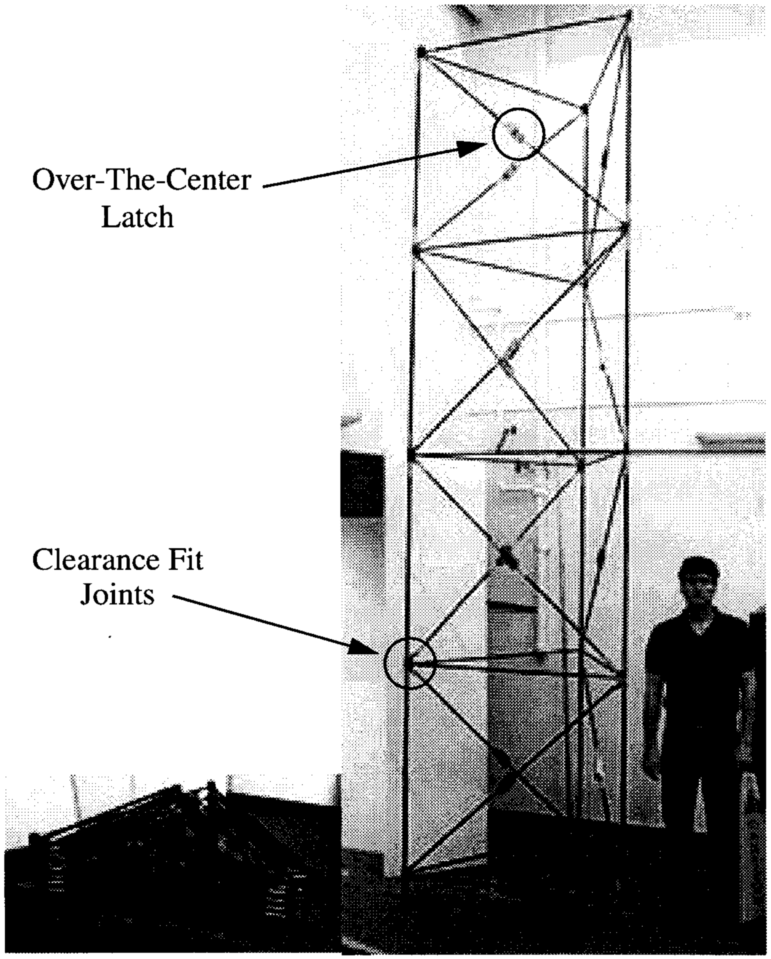
Microdynamics influences deployment repeatability and determines the micron-level linearity

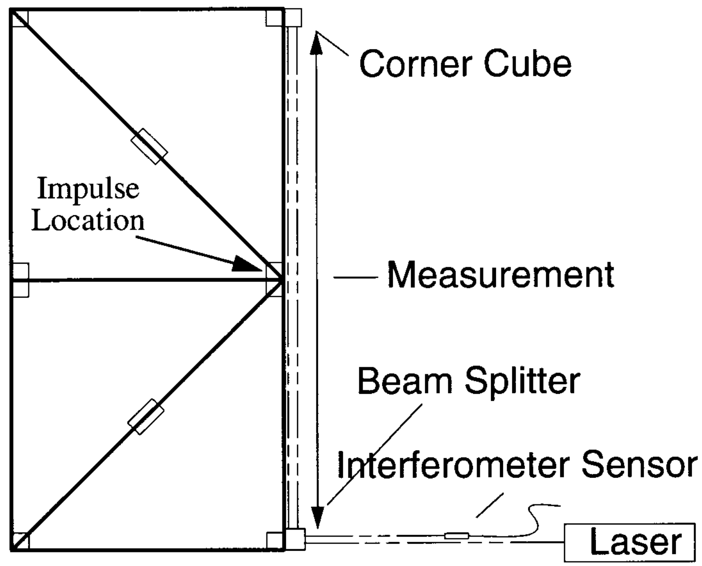
Several Microdynamic Effects are of Experimental Interest

- **Mechanical Instabilities**
  - Microlurches
  - Discontinuous elasticity
- **Thermal Instabilities**
  - milli °K "nanoquakes"
  - "singing materials and structures"
- **Nonlinear-in-the-small**
  - Inadequacy of linear models at small motions
  - "Damping goes to zero"
  - "Damping goes to infinity"
  - Transition from microscopic quantum interface mechanics to macroscopic material, component and whole-structure behavior.

This paper studies the induced progression of microdynamic instabilities known as "microlurches."

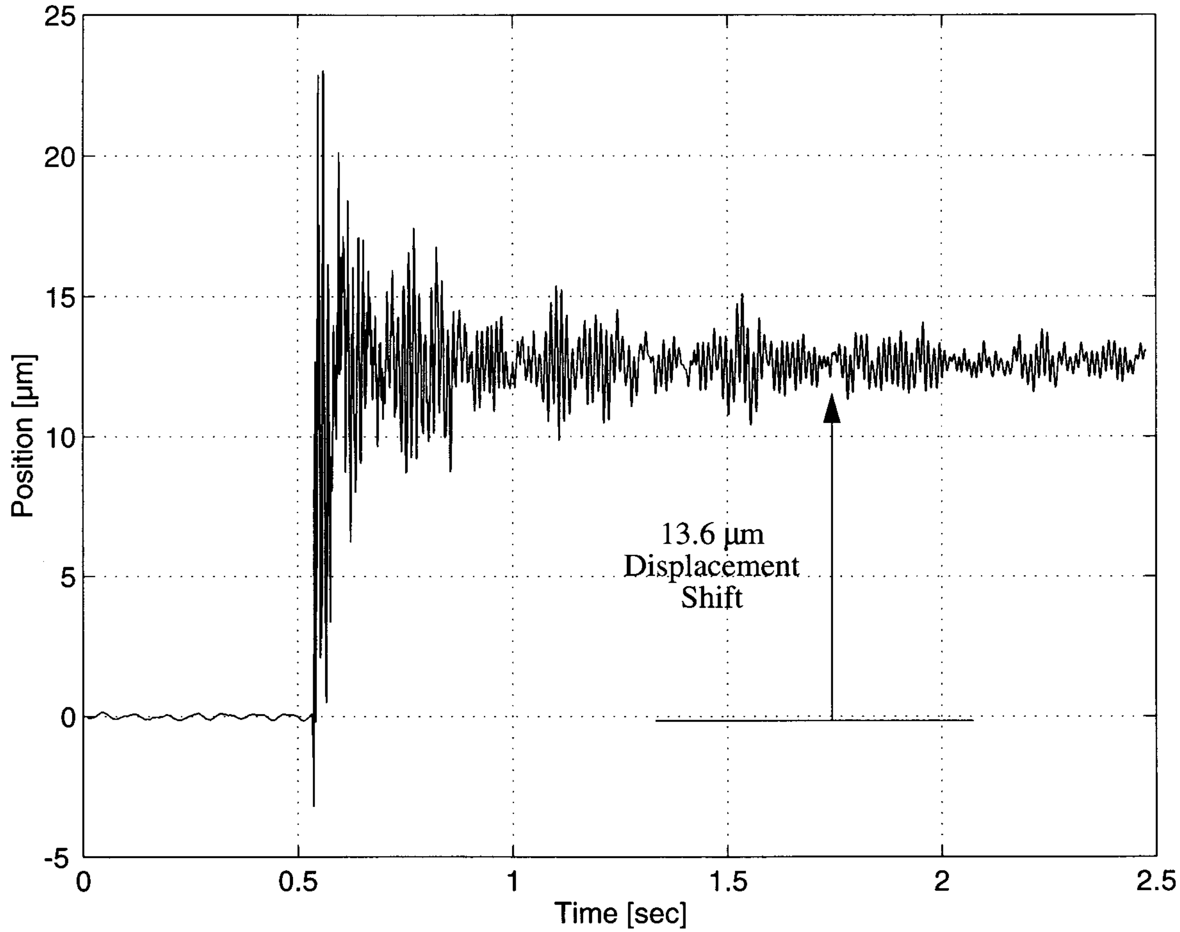
Mini-Mast Testing





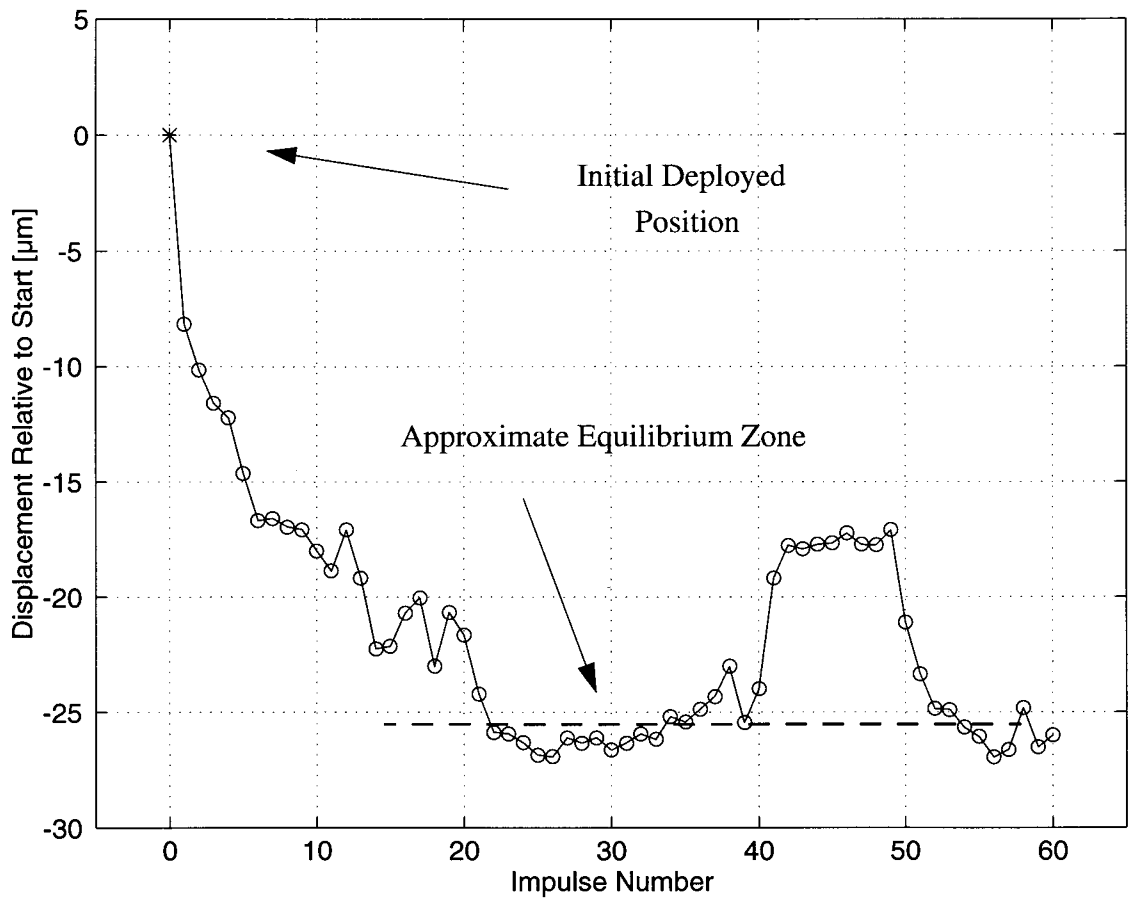
Mini-Mast Testing Measured the Post Deployment <u>Displacement</u> of One Dimension of the Structural Shape

Mini-Mast Testing Identified Micro-Lurch Phenomenon



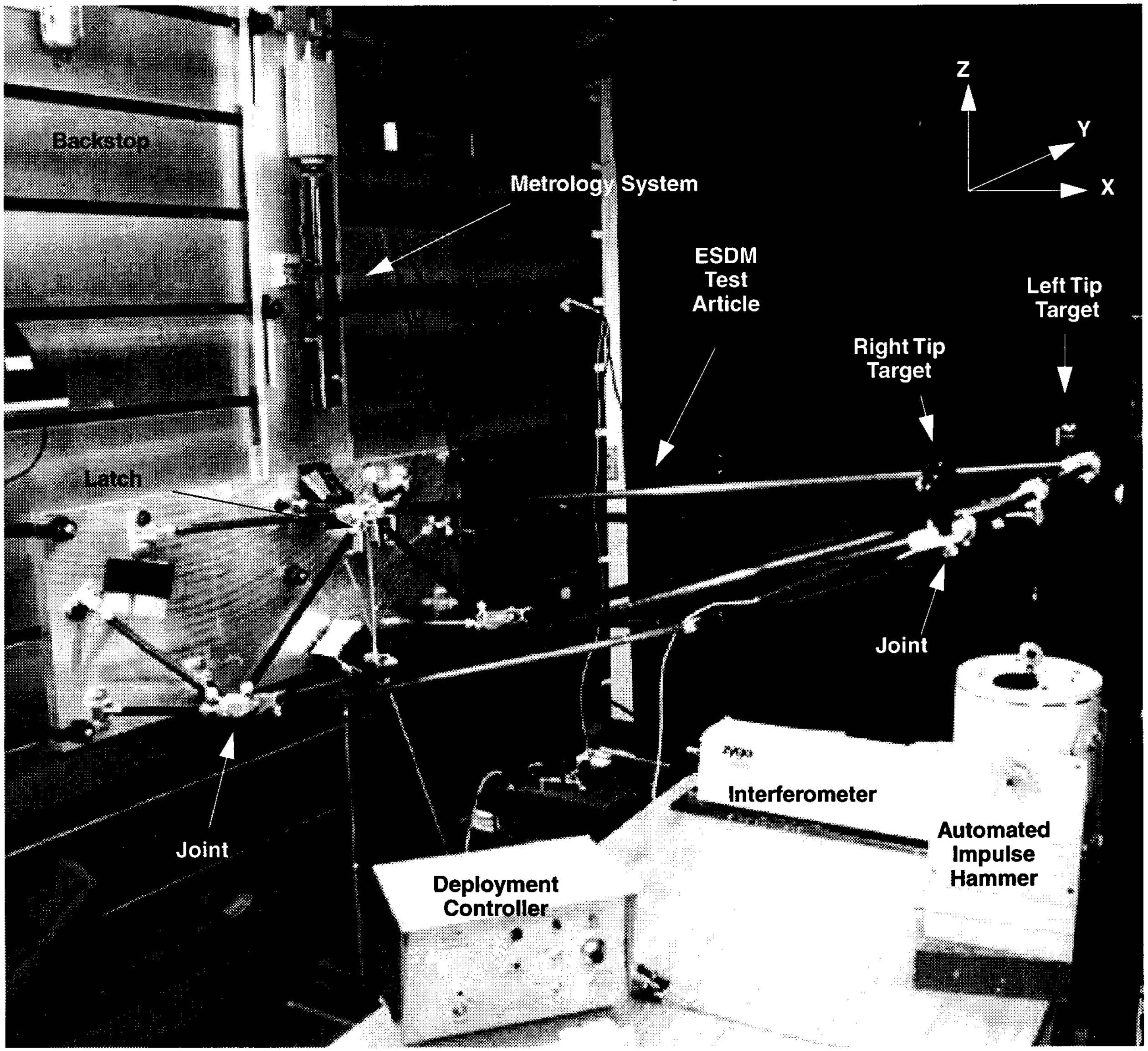
Micro-Lurch is a Change in the Static Shape of a Structure in the Response to a Transient Dynamic Disturbance

Mini-Mast Testing Also Identified Equilibrium Zone Phenomenon



The Equilibrium Zone is the Family of Shapes Towards Which Successive Micro-Lurches Migrate.

ESDM Test Configuration



Isolation of Micromechanics Required New Experimental Equipment and Protocols

- Positional Metrology System
  - Measures multiple points on structure
  - Uses reference target to provide absolute positional measurement
  - Measures both horizontal and vertical degrees of freedom
  - 10nm standard deviation

- Thermal Isolation and Compensation
  - Active thermal control
  - Thermal isolation with the controlled environment
  - High precision thermal measurement
  - Thermal deformations compensated

- Experiment Controls
  - Automated structure retraction and deployment
  - Automated impulse hammer for disturbance input

Positional Measurement System

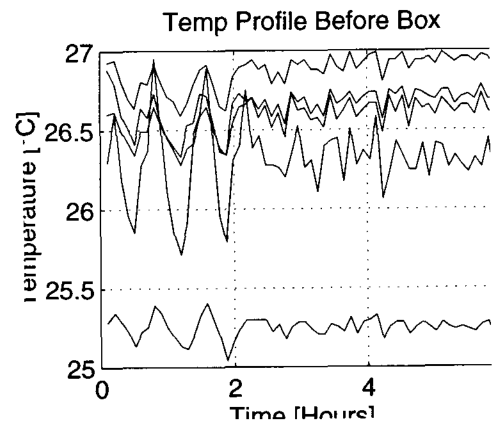
- Based on extraction of positional shift from image data
  - Video camera provides digitized image data
  - Averaging of multiple images reduces effects of CCD noise
  - Cross correlation with datum image provides phase shift peak
  - Bicubic interpolation provides 1/1000 pixel resolution
- Long distance microscope provides high magnification
- Partial field of view mirrors provide viewing of multiple targets
  - Two targets on structure
  - Reference target at base of structure
  - Subtraction of "white" target data removes mirror illumination effects
- In-situ calibration determines image shift - target motion transformation
- Use of reference target reduces effects of camera motion

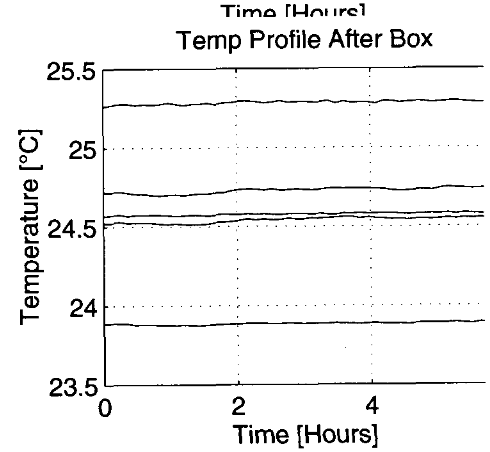
When combined with the thermal isolation and compensation system, measurement error standard deviation < 10nm

Thermal Isolation and Expansion Compensation Techniques

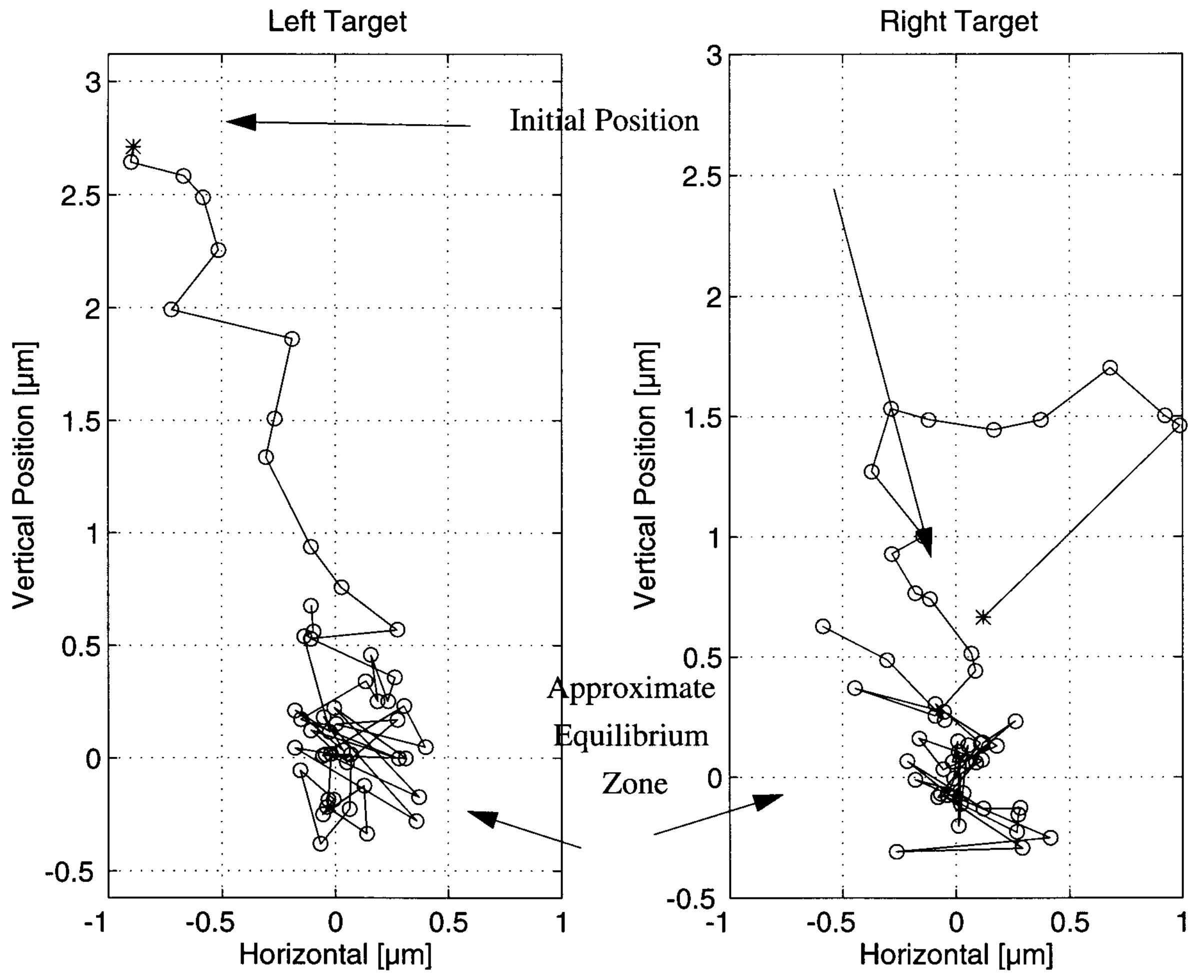
- Active Thermal Control
  - 2,200 cubic foot, 2 story room
  - Ostensibly 2°C control
  - Control vents impinge on test apparatus
- Thermal Isolation Chamber
  - 3" foam board insulation encloses test apparatus and backstop
  - R24 building material
  - Lowers temperature standard deviation to 0.2°C
- Thermal Measurement and Expansion Compensation
  - 27 solid state temperature sensors
  - In-line capacitive filters
  - Output averaging to reduce noise
  - Resulting temperature measurement standard deviation 0.003°C
  - Remove remaining structural motion using linear regression of temperature measurements to undisturbed motion

The Thermal Isolation Chamber (TIC)



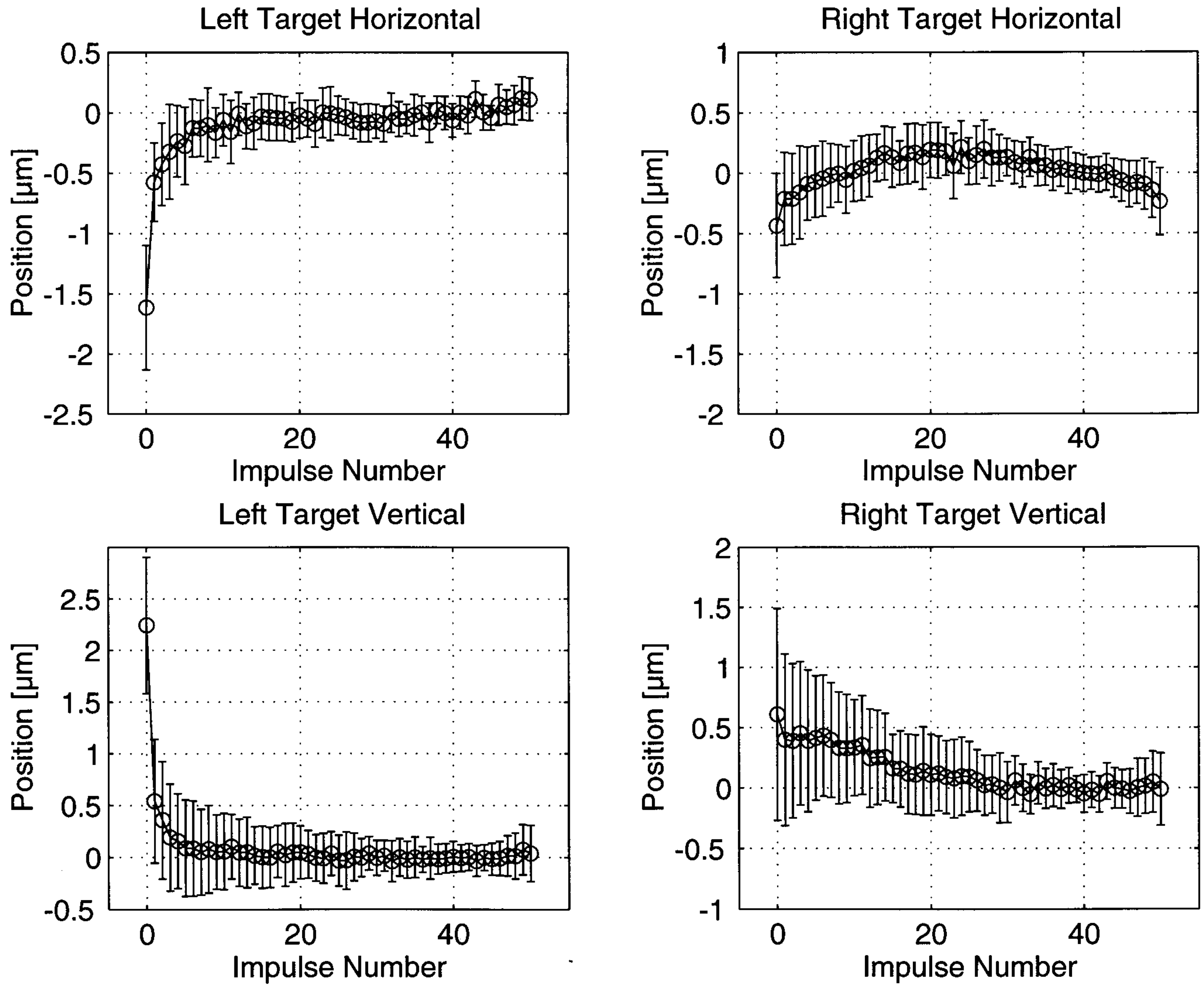


Example of ESDM Post Deployment Behavior



Both Micro-Lurch and Equilibrium Zone Occur Simultaneously in Multiple Dimensions

Mean Trajectories to Equilibrium Zone Indicate Sub-Micron Stabilization

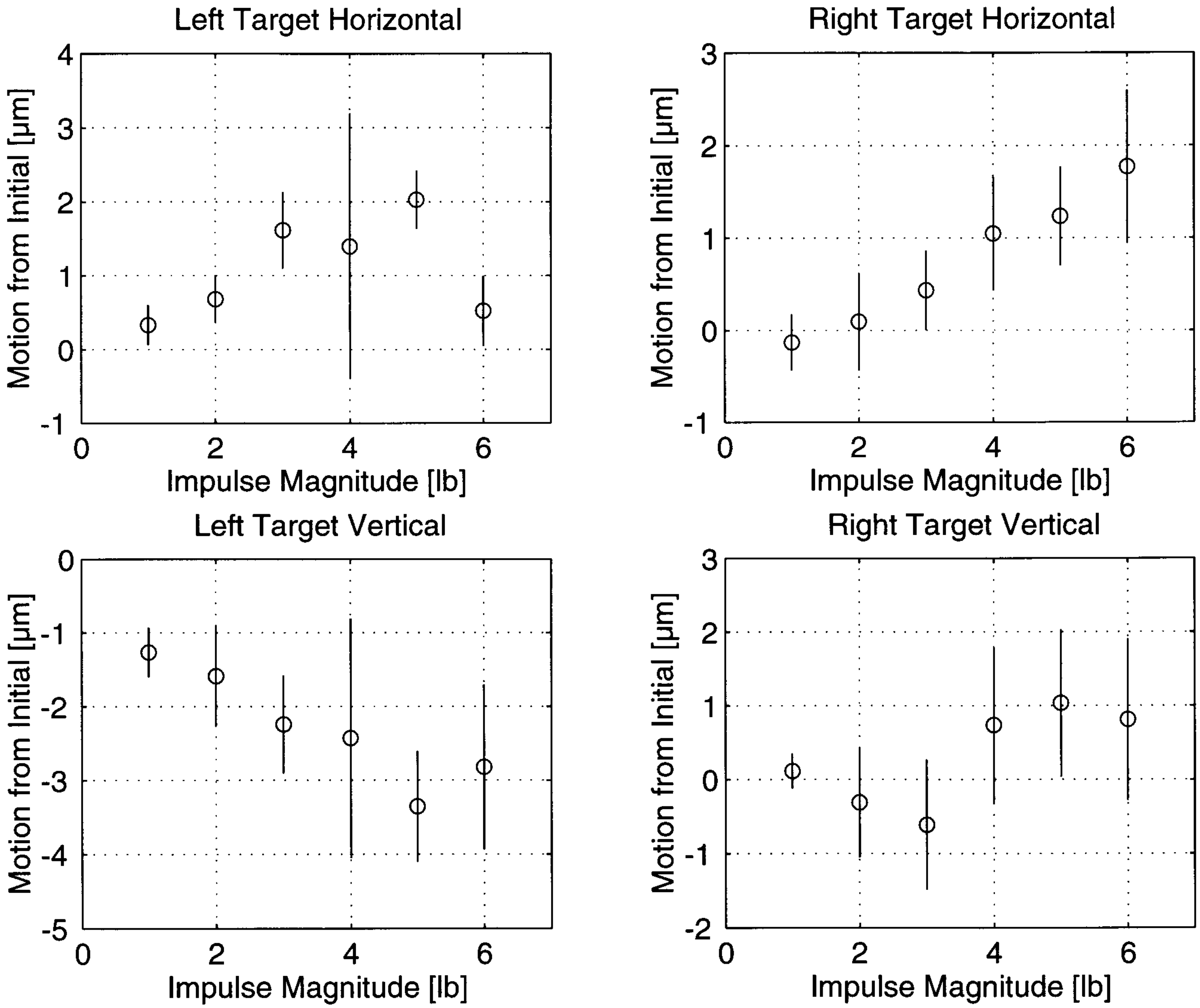


The Width of the Equilibrium Zone is Independent of Impulse

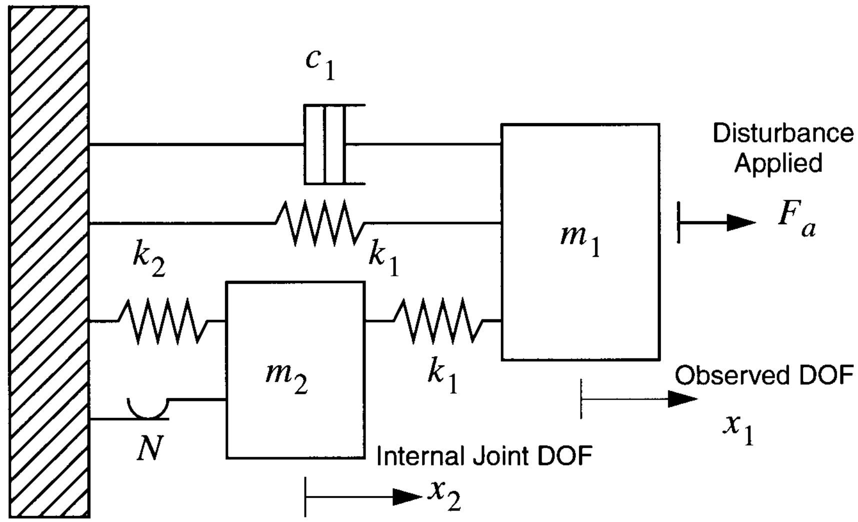
Impulse Magnitude [lbf]	Left Target σ_Y, [μm]	Left Target σ_Z, [μm]	Right Target σ_Y, [μm]	Right Target σ_Z, [μm]
0	0.20	0.27	0.25	0.27
1	0.12	0.20	0.19	0.18
2	0.19	0.30	0.22	0.24
3	0.15	0.23	0.21	0.22
4	0.43	0.28	0.21	0.24
5	0.17	0.23	0.20	0.23
6	0.24	0.26	0.23	0.28

The Conclusion Drawn from This Data is That the Structure Goes to a Single Point, Not to a Zone.

Mean Motion is a Nonlinear Function of Impulse Magnitude



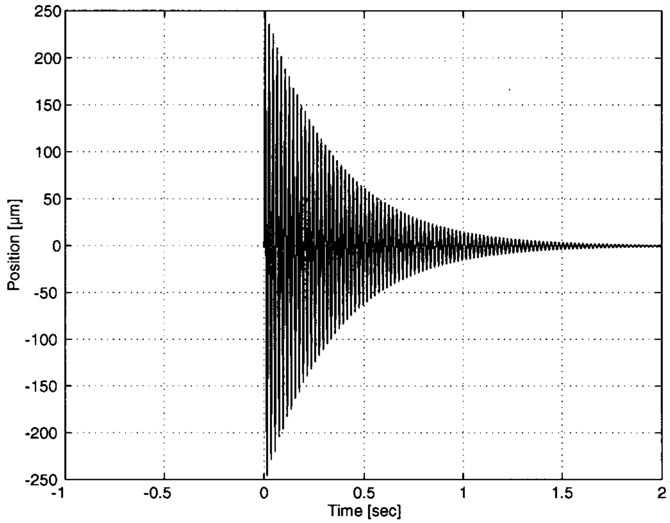
Phenomenological Model Used to Validate Experimental Results



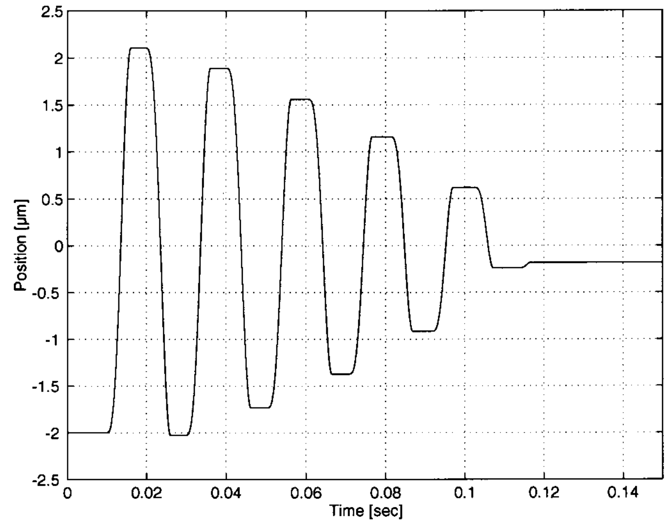
Such phenomenological models are useful for validating non-dimensional dependencies in experimental results.

Model Exhibits Microlurching and Equilibrium Zone Behavior

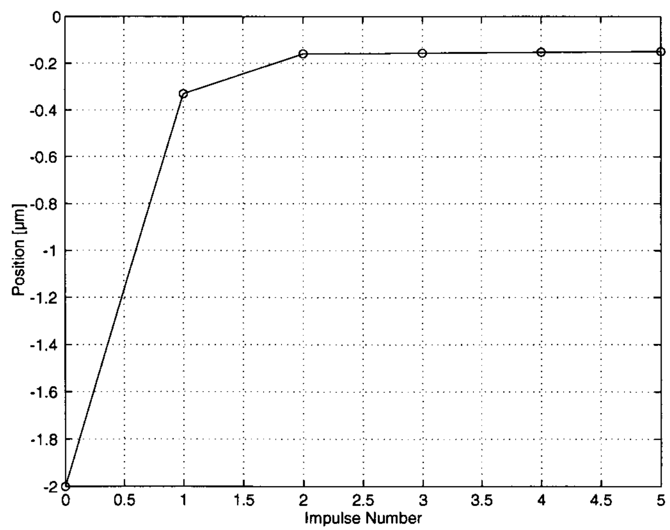
Simulated Free-Decay



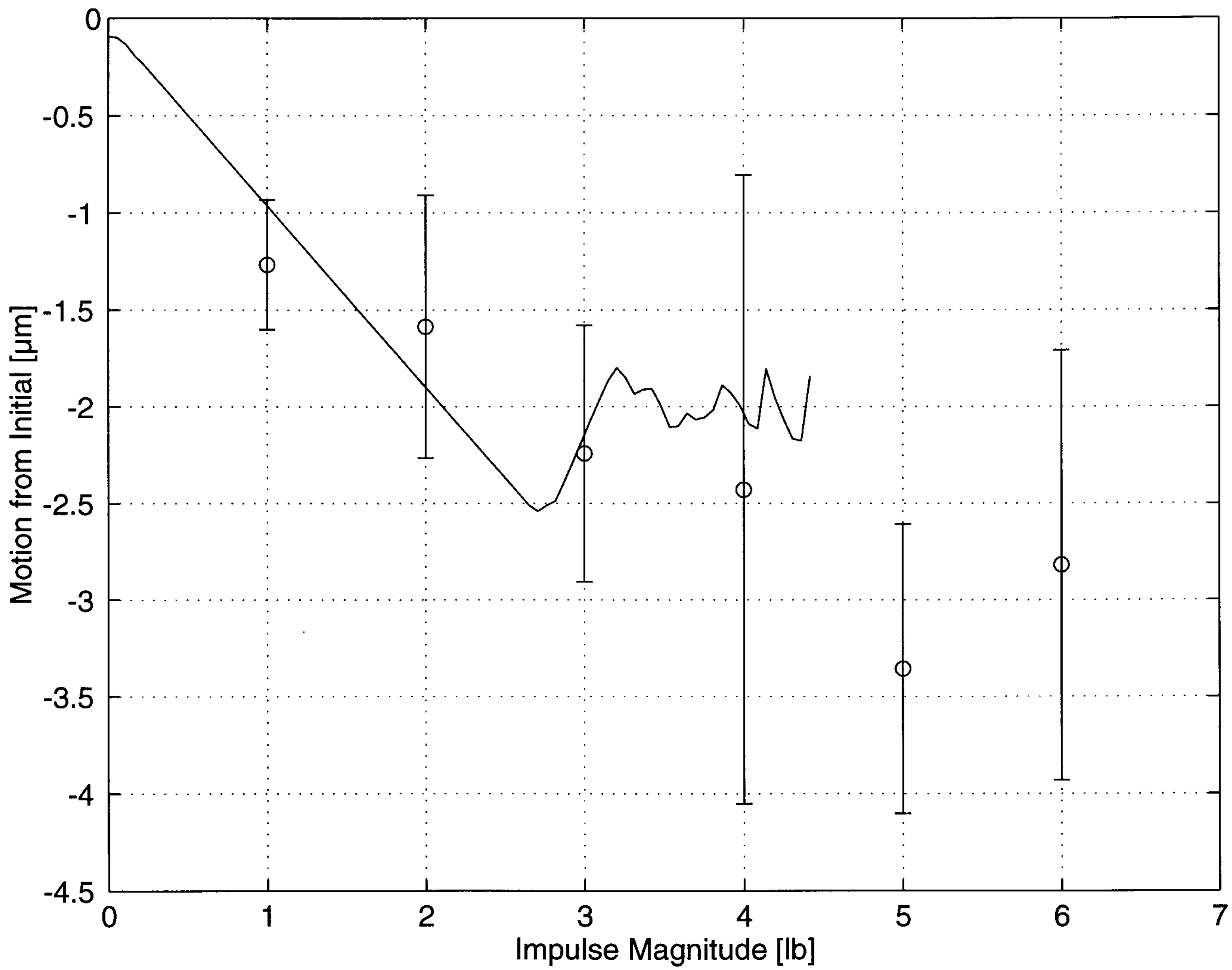
Microlurches in the Nonlinear Subsystem



Equilibrium Zone Progression



Model Correlates with Data



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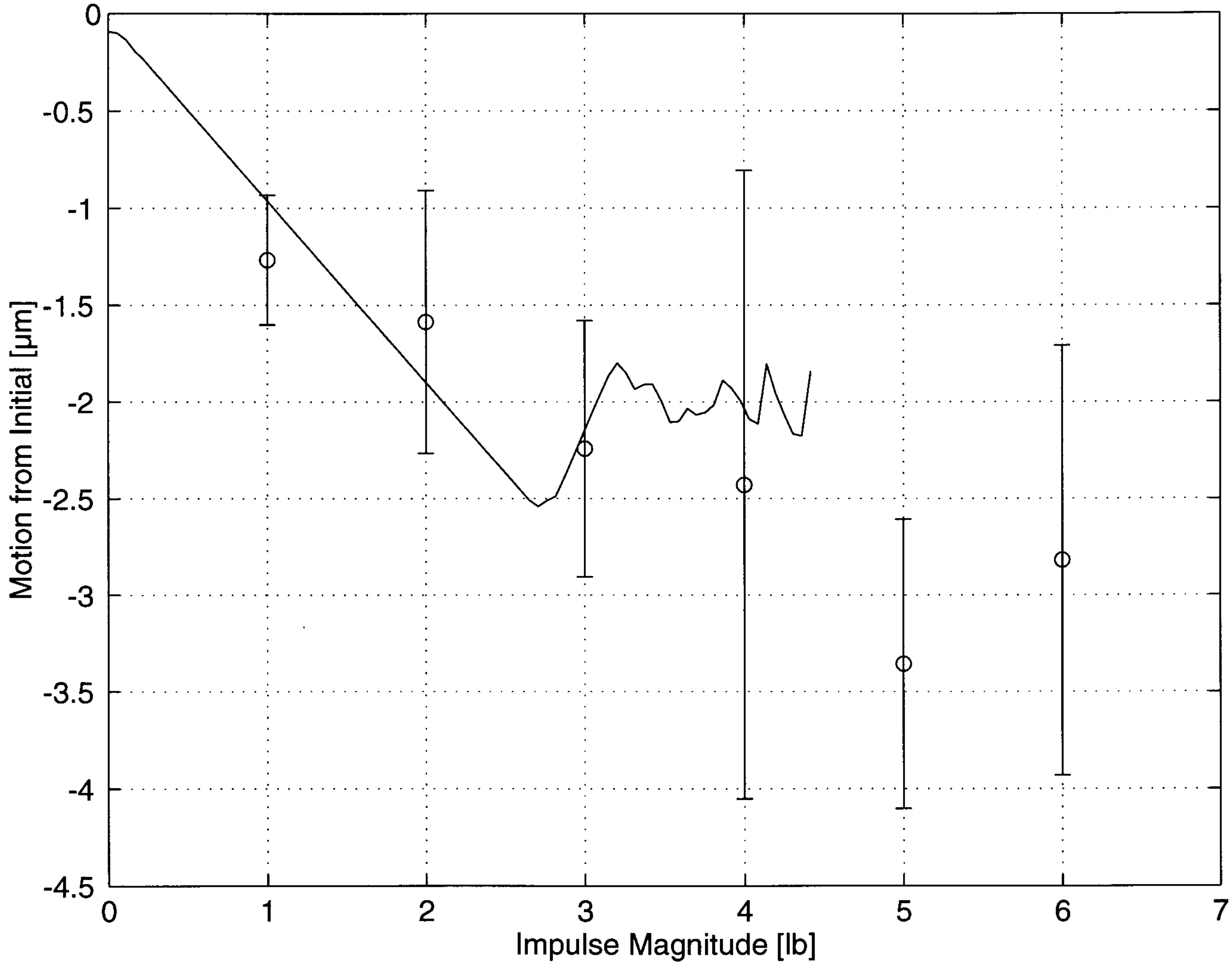


Summary and Conclusions

- **Microdynamic stability of deployed structures critical to ensuring instrument performance.**
- **Presented <1μm resolution data on a 1-meter deployed truss**
  - Very light preload in the latch
  - Ball bearing joints
- **Progression of microlurches used to indicate stabilization of the structure post-deployment to the resolution of the metrology system and test apparatus**

Current Research Activities in Precision Deployables

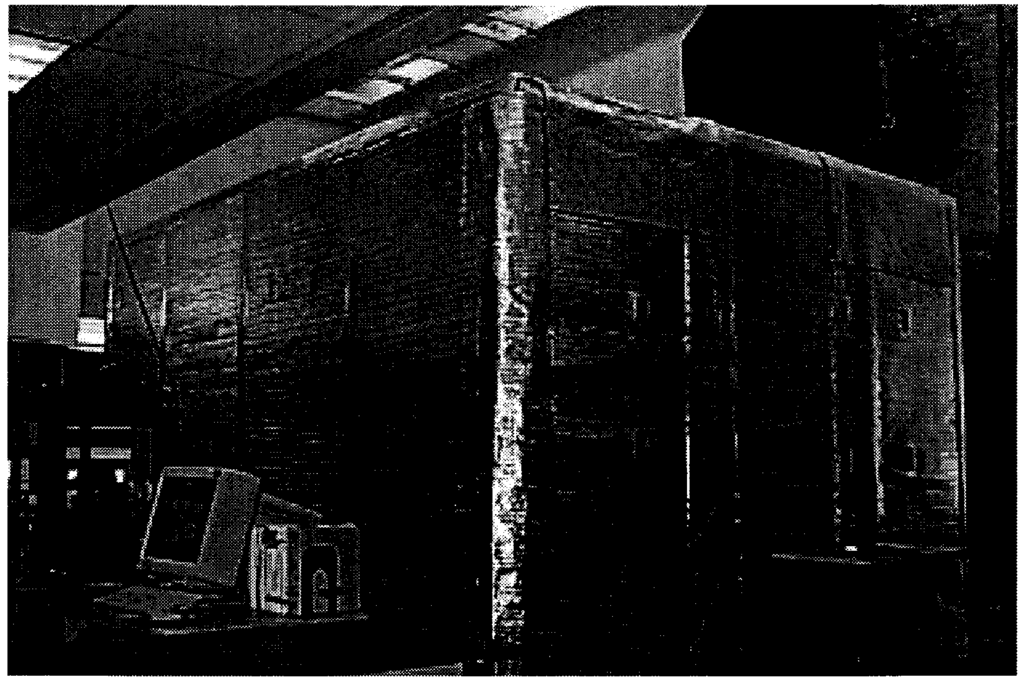
- **New facility for microdynamic experiments**
  - <10μg vibration/acoustics
  - milli °K thermal stability
  - nanometer resolution metrology
- **Microdynamics of a hybrid-fiber composite strut**
- **Nanomechanical models of joints and latches**
  - Non-coulombic friction models of joints and latches
  - Basic measurements of friction in preloaded latches under sub-micron motion

Significant errors in Coulombic models overstate nanomechanical imprecision. Preload does not make a joint precise.

- **"Space-Station Based Micron Accuracy Deployment Experiments *(MADE)*"**
  - ISSEC Phase A

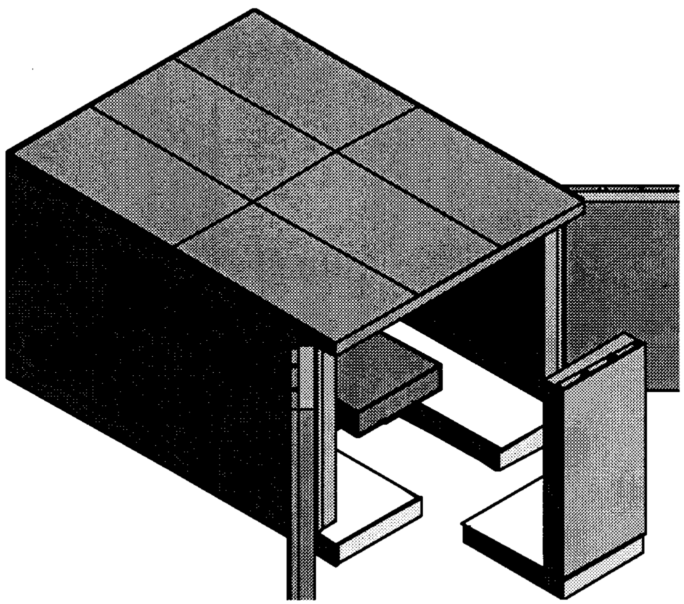
Microdynamic Testing Requires Extraordinary Measures

- Commonly ignored environmental effects can confound test results
- Passive thermal shielding and stabilization
- Acoustic shielding
- Ground vibration isolation
- High resolution temperature measurement
- Dynamic nanostrain measurement

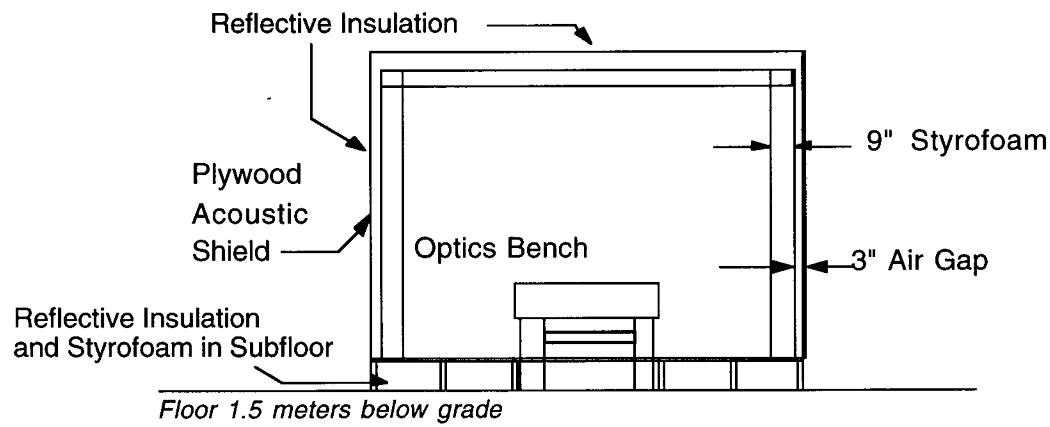


µD Test Facility at University of Colorado

Chamber Encloses 3-Meter Workspace

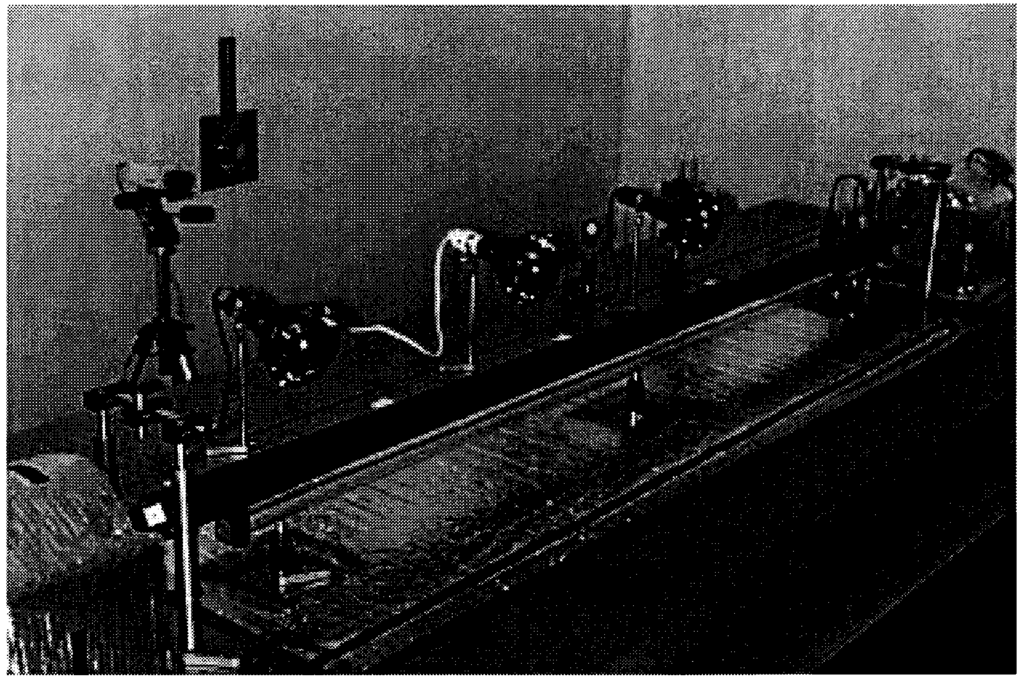


- **Access doors seal "draft-tight"**
  - All 6 sides insulated (~R 50)
  - ~1 hour thermal time constant for air
  - ~24 hour time constant for test articles
  - +/- milli °C/hr
  - +/- 0.1°C/day
- **Optics bench**
  - ~ 1μg during quiet period
  - ~ 50 μg from human speech



Thermal Cycling Test Configuration

- **Strut supported on thin vertical flexures**
  - 3” x 0.064” steel
  - No other loads applied
- **IR heat lamps**
  - 250 Watts each
  - Spaced between temperature sensors

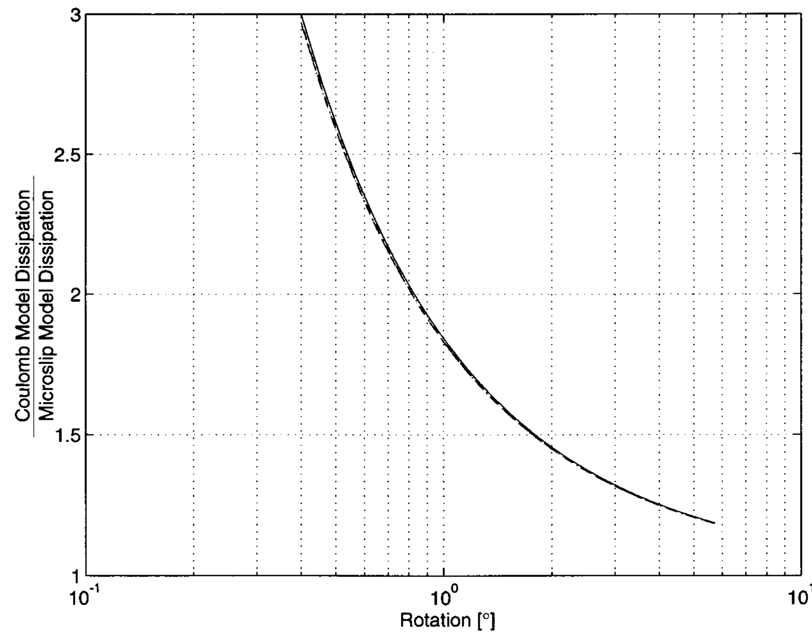


- **Measure strain with interferometer**
  - 2.5 nanometer resolution

Careful thermal and mechanical testing has not yet observed nanomechanical anomolies.

Coulombic Friction Theory Fails for Precision Deployable Structures

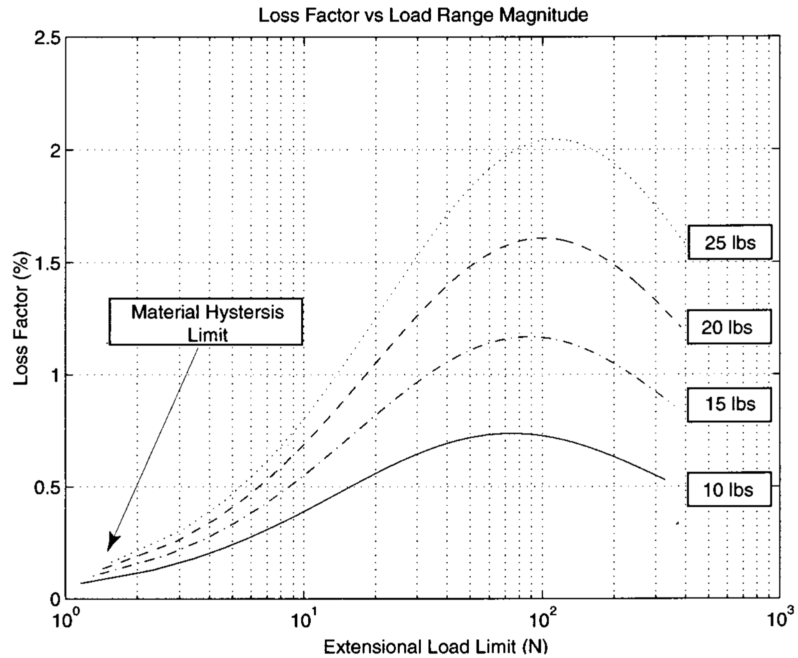
- **Coulombic theory incorrectly ...**
  - Suggests more preload is better
  - Suggests preload eliminates microdynamics
  - Predicts friction is proportional to preload
  - Overpredicts nonlinearity in joints and latches
- **Plot compares Coulombic model nonlinearity to microslip model nonlinearity**
  - Models agree at large motion
  - Models disagree at small motion
  - Preload does not affect the error



Precision deployable mechanism design must use correct friction models.

High Fidelity Analytical Model of LaRC Joint Predicts Counter Intuitive Behavior

- **Plot shows loss factor nonlinearity for a microslip model of LaRC precision joint**



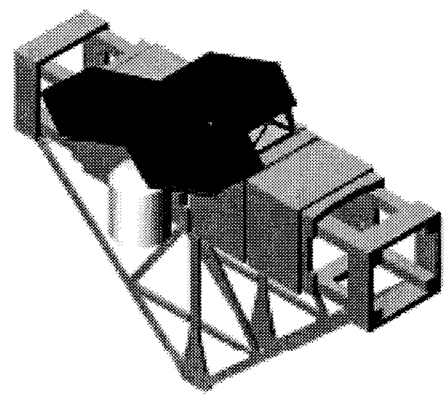
- **Model features**
  - Distributed microslip friction over Hertzian contact patches
  - Includes interface compliance of the contact patch
- **Model suggests ...**
  - Increasing preload increases the dissipative nonlinearity.
  - At low loads (sub-micron motion) the joint nonlinearity approaches material hysteresis (agrees with Bullock, Peterson & Lake, 1996 tests).

Model predicts "hysteresis collapse" in the LaRC precision joint under submicron motion.

Simple joints with moderate preload can be high precision.

Space-Station-Based Micron Accuracy Deployment Experiments *(MADE)*

- **Recent Phase-A selection in the International Space Station as an Engineering Center (ISSEC) program**
- ***MADE* will define and construct a reusable facility for long term study of precision deployable structures in 0-g**
- **Experimentally characterize**
  - Microdynamics of materials, joints and latches in 0-g
  - Deployment precision of deployable reflectors and trusses
- **Features**
  - External attached payload
  - Thermal shielding
  - μ-g vibration isolation
  - Nanometer metrology



Early *MADE* Test Article Concept

***MADE* will validate low-cost, lightweight high precision deployable technology.**